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on

ADVANCED METHODS FOR THE DYNAMIC CONTROL OF HIGH PERFORMANCE ROBOTIC DEVICES AND MANIPULATORS WITH POTENTIAL FOR APPLICATIONS IN SPACE

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I. SUMMARY AND INTRODUCTION

In the future robotic manipulators are expected to perform important tasks in space, such as servicing satellites. Current technology requires that tasks such as the repair, construction and maintenance of space stations and satellites be performed by astronaut Extra Vehicular Activity (EVA). Eliminating the need for astronaut EVA through the use of space manipulators would greatly reduce both mission costs and hazards to astronauts. Such applications introduce a number of manipulator control problems not commonly found in todays industrial manipulators. New control techniques must be developed to achieve good performance under such conditions. This is the final report of a three-year research program which was designed to advance state of the art space manipulator system control.

The first set of problems in space manipulator control results from the fact that space manipulators will be carried by free floating spacecraft, as shown in Figure 1, and will be working on other spacecrafts or space stations. The manipulator system and the objects it will be working on are not fixed relative to each other. The dynamic coupling between the manipulator and its environment greatly complicates the manipulator control problem. If a manipulator is mounted on a spacecraft, the motions of the manipulator will disturb the position and orientation of the spacecraft through dynamic coupling. If the manipulator motions are planned assuming that the spacecraft does not move, then the actual end effector motion will not follow the desired paths. Also the manipulator's ability to reach desired points is significantly effected by the spacecraft motions. In other words the manipulator's "workspace" must be analyzed - considering the spacecraft motions. Finally, if spacecraft must hold its attitude or location in space, inspite of the manipulator motions, and if the spacecraft's attitude control jets are used to hold its position, large amounts of reaction fuel could be used. This might severely limit the on-orbit life of the system. The solution to these problems requires the development of new control techniques.

The second set of control problems for space manipulators results from the highly unstructured space environment. This unstructured environment will make the obstacle avoidance problem more complex. It may also lead to the design of redundant manipulator systems that can reach around obstacles. The control of such redundant manipulators mounted on free floating bases is a challenging problem. Complex tasks in the unstructured space environment will also require the coordinated use of more than one manipulator. This too, introduces control problems which have yet to be solved. Lastly, manipulators operating in such unstructured environments will require substantial amounts of sensory information for control. This information will most likely be provided by machine vision systems and other sophisticated sensory systems. While substantial research is being done to increase the speeds of such systems, it is not likely that in the near future their speeds will be high enough to achieve high performance using conventional manipulator control strategies.. We believe it is possible to develop control strategies which can use relatively limited amounts of sensory data more effectively to obtain good performance.

Finally, the weight limitation placed on space systems will require that these systems be far more flexible than industrial systems. The coupling between the spacecraft and the manipulator, the objects being manipulated, and in the manipulators themselves, will have some flexibility. The consequences

Figure 1

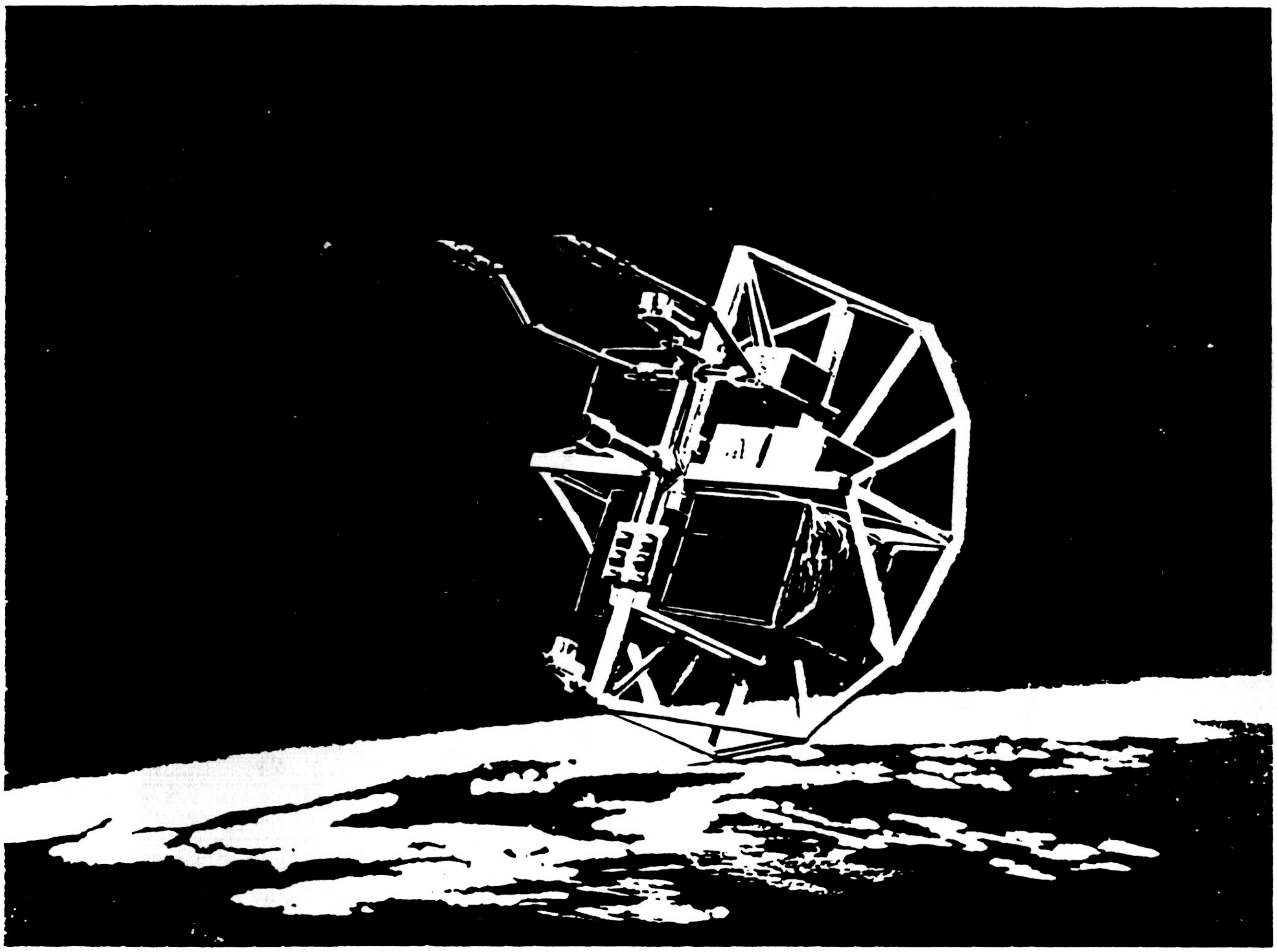

Figure 1: A Space Manipulator System Concept

of such flexibility are to degrade the positional accuracy of the manipulator, reduce end effector stiffness and in some cases make the systems unstable. As a result new control techniques will be required.

While a great deal of research has been done on dynamic control of industrial manipulators, very little work has considered the special problems associated with the operation of manipulators in space. The thrust of this research program was to study these problems and develop solutions to them. As discussed below, this work has resulted in the development of some powerful analytical tools for studying manipulators in space; principally a theoretical concept called the Virtual Manipulator. We have also made important progress in developing simulation packages and a major experimental facility for developing and evaluating control algorithms for manipulators mounted on vehicles, such as spacecraft. We believe that this experimental facility, which is called a Vehicle Emulator System (VES), is a unique and powerful tool.

II. BACKGROUND

A number of researchers have studied the potential application of robotic manipulators in space (Akin et al., 1983, French and Boyce, 1985, Bronez et al., 1986, JPL Proceeding, 1987) and established some of the required capabilities for these systems. Future space manipulator systems consist of a spacecraft with one or more mechanical arms, such as shown in Figure 1. The spacecraft will be capable of motion in six degrees-of-freedom, and will have reaction jets for position and attitude control. The manipulator joints could be driven by photovoltaicly powered electric actuators, which use no reaction fuel. The manipulator motions will, in general, disturb the spacecraft's position and attitude and this will result in the consumption of reaction jet fuel. The useful life of a spacecraft system is often limited by the amount of reaction jet fuel it can carry. For this reason, it is very important to plan manipulator motions which minimize spacecraft motion and hence minimize the amount of reaction fuel consumed. This is just one of the problems which needs to be solved in order to successfully use manipulators in space.

While there has been a great deal of research on the kinematics, dynamics and control of industrial manipulators (Lee et al., 1986), relatively little has been performed on space manipulator systems. The dynamic behavior of industrial manipulators is inherently different from space manipulators, because space manipulators interact with free floating objects. Therefore, much of the research reported in the literature for industrial manipulators can not be applied to space manipulators.

Space manipulators are similar in some ways to mobile manipulators, such as underwater and vehicle based manipulators. Mobile manipulators also have moving bases. They differ from space manipulators, however, because their environments provide substantial constraints to vehicle motions (Tanner, 1987, Khatib, 1985, Li and Frank, 1986), and the cost of their maneuvering efforts are not as critical as space manipulators; hence the focus of this research is quite different from that reported on here. Much of the mobile manipulator work has addressed the teleoperator control issues.

In fact much of the past research on the control of manipulators in hazardous environments, such as underwater, nuclear industry and space, has assumed that the systems will be teleoperator controlled (Sheridan, 1986, Lee et al., 1985).

This work has not generally considered the manipulator-vehicle dynamic coupling nor the effects of system flexibility. The effects of limited sensory data have been considered, but from the human operator point of view. Future space manipulator systems will most likely contain some degree of teleoperator character, but it would be most effective if this were at a high supervisory level. The lower level control issues, such as the dynamic control and path planning, would ideally be autonomous functions. This would relieve the operator from tedious, difficult and nonintuitive low level control functions, such as compensating for space dynamics. The human operator would then be able to devote his entire attention to higher level decisions. Hence, teleoperator systems would benefit from high performance manipulator automatic control techniques.

Little research has been done on the automatic dynamic control of space manipulators (Meintel and Schappell, 1982, Kohn and Healey, 1986) and with a few exceptions (Longman et al., 1985, Lindberg et al., 1986) the spacecraft-manipulator dynamic interactions are neglected. Researchers of space manipulators have focused on issues such as computer control systems, sensing and, as discussed above, telerobotics. As a result of our past research, sponsored by NASA and discussed in the next section, a general approach for modeling the kinematics and dynamics of space manipulators has been developed (Dubowsky and Vafa, 1986, Vafa and Dubowsky, 1987a - 1987c). In this research manipulator workspaces are analyzed and algorithms for their forward and inverse kinematic solution are developed.

As discussed earlier, flexibility is an important issue in the dynamics and control of space manipulator systems. Space manipulator links, such as the space shuttle arm, are very long and lightweight. Therefore, they will be flexible and difficult to control. Also when a space manipulator system attaches to another vehicle or space station, see Figure 2, the means of attachment or docking mechanisms will have flexibility, which makes the precise manipulator control difficult. Substantial research has been done to develop methods to model manipulator flexibility (Sunada, 1980) and methods have been proposed to compensate for manipulator flexibility (Cannon and Schmitz, 1984, Book et al., 1985). Even so, the control of flexible manipulators has not been resolved and is currently being investigated. In addition, none of these flexible control studies have considered the effects of spacecraft motions.

Based on our review of the state-of-the-art, we believe that research is still required to develop advanced control techniques to insure that future robotic devices will be operated effectively in the uncontrolled and unstructured environment of space.

III. REVIEW OF PROGRESS

The goal of our work was to develop advanced control methods for robotic manipulators in space environments to enable these systems to meet their missions. The first objective was to define the control system performance necessary for the successful operation of space manipulators. Based on this work, which was largely completed during the first year of the program, (see our first annual report), it was concluded that control requirements of space manipulators are quite different from current industrial applications. The work also revealed some significant control research issues that need to be addressed before manipulators can achieve high levels of performance in space. These

Figure 2

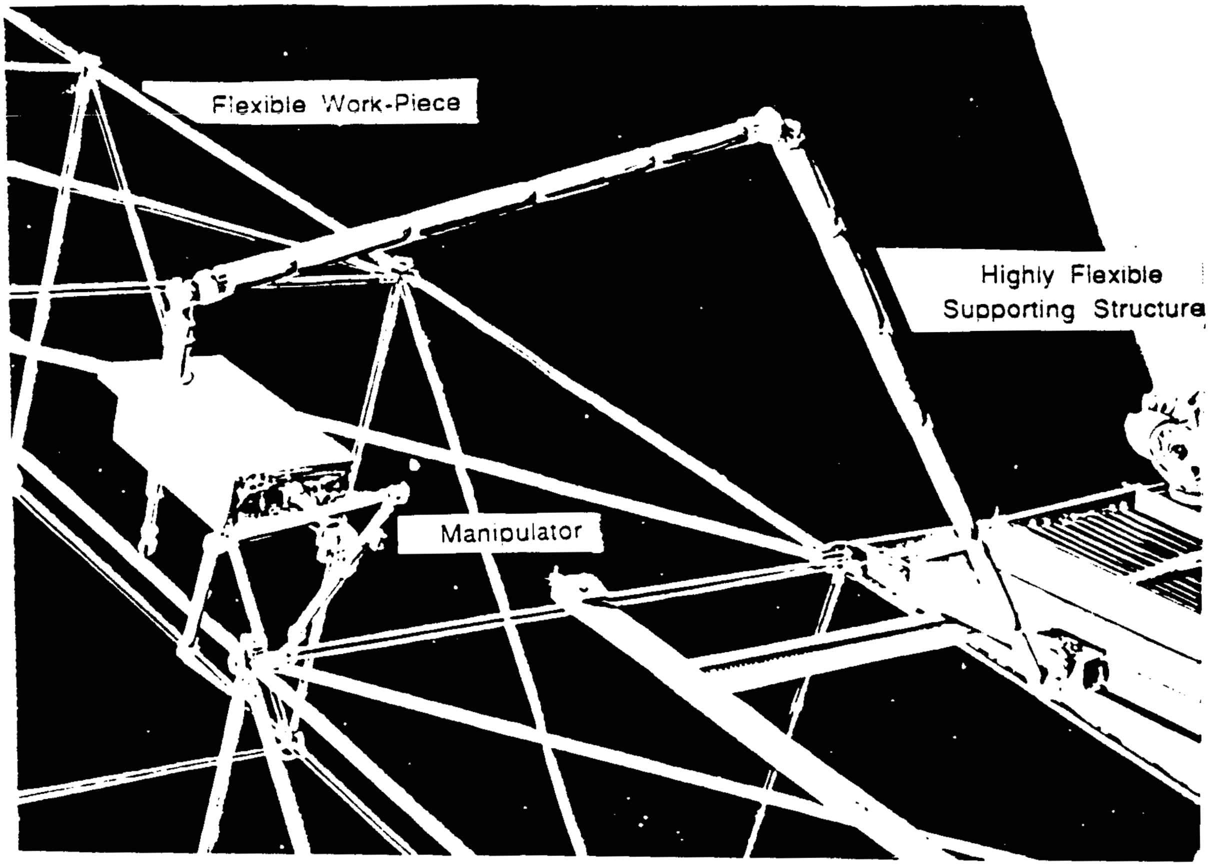

Figure 2: A Space Manipulator Mounted on a Highly Flexible Structure

results have provided our research direction during the second and third year of the program. The results of our work are briefly described in this report. The attached appendices and our first two annual reports contain more detailed descriptions of our activities.

A. Analytical Studies

1. An Overview

Our earliest analytical studies focused on defining some of the major dynamics and control problems which would be encountered by space robotic systems. In this work a series of potential robotic tasks were defined and studied (see Annual Report I). Based on the results obtained, certain key gaps in the technology required to successfully complete these selected tasks were identified, and selected as the focus of our work later in the program. The progress made in these areas during the concluding program is summarized below.

2. The Virtual Manipulator Concept

As discussed above, the application of manipulators in space is complicated by the manipulator-spacecraft dynamic interactions. For example, a space manipulator's motions will disturb the attitude and location of its spacecraft. This phenomenon makes it difficult to control the manipulator and adversely affects the manipulators precision. In addition the orbit life of the system is reduced by requiring excessive amounts of reaction jet fuel. These problems had not been addressed by researchers working on the space application of manipulators. As part of the research under this program a new concept for space manipulator modeling was developed, which is called the Virtual Manipulator (VM). The Virtual Manipulator is an idealized kinematic chain whose base is fixed in an inertial space at a point called the Virtual Ground (VG). The VG is located at the center of mass of the complete system: the manipulator, vehicle and payload. Virtual manipulators exist for different manipulator structures, such as open or closed chains, single or multiple arms, revolute or prismatic joints, or any combination of these structures.

It has been shown (see Appendices VI, VII, VIII) that the kinematic and dynamic properties and motions of the complete system can be described in terms of the VM motions. Because the VM base is fixed in inertial space it greatly increases the planner's ability to understand the complex motions of free floating manipulator systems. Use of the VM simplifies the kinematic and dynamic analysis. VM's can be used for space manipulator inverse kinematics, workspace analysis, design, control synthesis and equations of motion formulation. It can also be effectively used for manipulator motion planning and control to minimize the degrading consequences of manipulator-spacecraft dynamic interactions. It should be noted that using conventional methods, these problems are far more difficult for space manipulators than for standard manipulators with fixed bases. In the following sections some of the applications of the VM approach are briefly discussed. For a more detailed discussion please refer to Appendices VI, VII, VIII.

a. Workspace Analysis

Since a space manipulator's motions will cause its spacecraft to move, the manipulator will have different workspaces depending on how the spacecraft location and attitude are controlled. If reaction jets are used to keep the spacecraft stationary, the method for finding the system workspace is similar to that for fixed based industrial manipulators (Yang and Lee, 1984). We call this work space the "fixed workspace". Generally, the workspaces of space manipulators will be smaller than the fixed workspace. In other words, a space manipulator will not have a reach as large as the same manipulator on earth with a fixed base.

For cases where the attitude, but not the location, of the spacecraft can be controlled, such as when reaction wheels are used, the workspace can easily be found using the VM. To do this a Virtual Manipulator is constructed to the end effector of the real manipulator. The joint limits of the real manipulator are transformed into VM joint limits. The workspace of the Virtual Manipulator is then found using conventional workspace analysis methods. The real manipulator workspace will be equal to the VM workspace.

To find the workspace of a completely free floating manipulator system, one which does not use reaction wheels or attitude control jets, one must note that the motions of the first VM link, representing the spacecraft, are not actively controlled, and the final spacecraft orientation is dictated by the paths chosen for the manipulator. Therefore, the points the manipulator can reach depend upon the initial position of the manipulator and the path it takes in attempting to reach a point. For this case we have defined the "free workspace" as the region that the manipulator is guaranteed to be able to reach, without regard for the spacecraft or manipulator initial orientation and path. The free workspace can be found using the VM approach. First, all VM workspaces corresponding to all fixed spacecraft orientations are found. The intersection of all of these workspaces forms the free workspace.

b. Inverse Kinematics

If the end effector position of a free floating space manipulator is specified in inertial space, standard methods for solving the inverse kinematic problem, needed for the manipulator's control, cannot be used. However because the Virtual Manipulator's base is fixed in inertial space the inverse kinematic problem can be solved directly using the VM. Assumming that it is possible to control the orientation of the spacecraft but not its location, a VM is constructed for the end effector. Then the inverse kinematic problem for this VM can be solved using standard methods, since its base is fixed in inertial space. This is equivalent to solving it for the actual manipulator, since the joint motions of the VM of a revolute system are identical to those of the actual system. With the joint variables obtained from the VM inverse kinematic solution, the real manipulator will reach the desired location in inertial space inspite of the spacecraft translations.

c. Path Planning

In certain cases rotations of the spacecraft as the manipulator moves are not acceptable. For example, spacecraft rotations may cause communication devices to lose their signals. It can also be shown that permitting the spacecraft to rotate reduces the manipulator's workspace. Spacecraft rotations can be controlled using reaction wheels or reaction jets. These devices have the disadvantage of increased mechanical complexity and increased system weight.

The manipulator motions can be planned using its VM so that the end effector moves along a nominal specified path and maintains an arbitrary spacecraft orientation without using any attitude control jets, or requiring reaction wheels. The final spacecraft orientation depends on the path taken by the manipulator from one position to another. Therefore, it follows that the final spacecraft orientation will change if the manipulator moves along one path in joint space and returns to its initial position by another path. It is similar to finding paths necessary for an astronaut to make a rigid body rotation (Kane et al., 1972). This leads to a strategy for adjusting or correcting motions of the spacecraft's orientation. In this strategy a nominal trajectory is selected for the end effector and spacecraft orientation. Then the joint motions are executed assuming the spacecraft remains stationary. If at any point the base orientation deviates from its desired path, a series of small cyclic motions, calculated to correct for the spacecraft orientation, are added to the nominal joint motions. The details of finding these correcting motions are described in Appendix VII.

In our work to date we have developed the concept of the Virtual Manipulator and have shown it to be useful in performing kinematic and workspace analysis for manipulators on spacecrafts. Our studies also strongly suggest that the Virtual Manipulator approach can be a very useful tool for developing planning and controlling techniques for manipulators in space.

3. Optimal Control

Space robotic manipulators will have to be designed with ultra lightweight structure and components. Much of the weight of manipulators is in their actuators. In order to perform tasks in reasonable time periods, with relatively small actuators, the manipulators motions must be time optimal. Manual planning of manipulator motions would generally fail to select the manipulator's time optimal motions. This would result in reduced effectiveness in space. Manual planning of minimum time manipulator motions is very difficult because manipulators dynamics are very complex.

In our work we have developed a method to time optimally control and plan manipulator motions considering the full nonlinear dynamics of the system, actuator saturation, workspace obstacles and limits on the manipulator's joint motions. The method is computationally efficient and permits mission planners to select weighting factors which gives flexibility in selecting the importance of maintaining a distance from a specific object or constraint. The method obtains the optimal open loop torques/forces and optimal joint positions and velocities for closed loop control. It has been implemented in a software package, called OPTARM II, with extensive interactive graphics capabilities which enhance its practical use. More detailed discussion of the technique are presented in Appendices II, III, IV and V.

We believe that the use of this time optimal control and planning approach will result in reasonable levels of performance with lightweight actuators. However, the structural elements of space manipulator systems and spacecraft will also be lightweight. This will introduce significant flexibility into the system's dynamic characteristics. We have developed modeling techniques for flexible manipulators.

4. Adaptive and Learning Control

Space robotic systems will rely heavily on vision sensory information for control, and for knowledge of their environments and payloads. We have investigated some of the control problems this causes and the potential solutions to these problems. In our early work, we focused on Model Referenced Adaptive Control methods to compensate for such factors as unknown payload characteristics. This work has been reported in our first and second annual technical reports. This report will briefly review our development of control algorithms for use with vision sensors.

It is likely that manipulator control system requirements will, for the forseeable future, push the limits of their vision systems. The data from these systems will appear to be sparse in time compared to control bandwidths. For this reason we have been developing control algorithms which would enable manipulators to use relatively low data rates to provide high performance. We have developed two approaches to achieving this capability. The first is based on learning control methods and the second is based on a model building technique.

Robotic manipulators have highly nonlinear dynamics and are subject to substantial disturbances, variable joint frictions, etc., which can result in unacceptable manipulator errors. To reduce these, a number of advanced control algorithms have been proposed. Unfortunately such algorithms can require extensive calculations. Recently, a class of control algorithms, called learning control, has been developed which exploits the repetitive nature of many manipulator tasks in order to compensate for these errors. These algorithms require less calculations than many other advanced control algorithms and they do not depend on accurate knowledge of manipulator dynamic models.

In the development of these algorithms it has been assumed that the errors used by the algorithms can be measured continuously along the manipulator's path. However, for systems using sparse data, our work has shown that the performance of these algorithms degrades. To eliminate this problem we have developed several techniques: a data shift algorithm, a forward estimation learning algorithm, and a forward and backward estimation learning technique. We have shown that these modified learning control algorithms can compensate for sparse data effects, yielding performance which approaches that of systems without sensory information limitations. These algorithms are explained in detail in Appendix IX.

We also investigated the use of models derived from sparse data for manipulator control. The approach uses the limited vision information to build a model of the process, which is used to control the manipulator. It was shown that relatively slow vision rates can be used to control relatively fast tasks. The concept was demonstrated experimentally by having the manipulator catch a cylinder rolling down an inclined ramp. The ramp angle was initially unknown as was the cylinder's initial velocity and starting time. It was found that even with measurement errors and noise, a regression based model building algorithm could successfully perform this task with very low data rates from the vision system. A second demonstration involved pushing an object across a horizontal plane. Here again the vision provided sparse position information which was used to build an analytical model of the process that could be used for manipulator control. Model building techniques developed in this work were found to be quite successful for these simple tasks. Their use for the control of more complex tasks with sparse data could lead to useful techniques for space manipulation. For example, controlling a manipulator which must grasp a free floating lost tool in space.

B. Simulations and Software Implementations

As part of our research we have written a number of simulation software packages to test and demonstrate the approaches being developed. The major efforts have been in the optimal control area, the VM approach and adaptive control studies. Typical of these is the OPTARM program which implements, in a Computer Aided Design (CAD) software package, the optimal control techniques we have developed. It has extensive interactive graphics capabilities, which enhance its practical use. The virtual manipulator approach has also been implemented in an interactive program which uses a high speed Iris graphics display to enhance the insights this method gives for understanding the behavior of manipulators in space.

We have also devoted substantial effort in rewriting our Finite Element flexible manipulator modeling program, called FLEXARM, to improve its computational efficiency.

C. Experimental Systems and Studies

During the latter part of this program we put substantial effort into developing of our experimental capabilities and using them to test, evaluate and demonstrate the results of our theoretical studies. We have designed, constructed and used a system for experimentally implementing manipulator control algorithms. We have also demonstrated a method, using a one degree-of-freedom system, for emulating manipulators carried on spacecraft. In addition, we have designed a six degrees-of-freedom system based on the same concept. These systems are described below.

1. Experimental Evaluation and Demonstration of High Performance Manipulator Control Algorithms

We have selected the PUMA 260 manipulator for our work in developing and testing control algorithms for space applications (see Annual Report I). We used a PUMA which was donated to us by the Westinghouse Corporation. Recently, we have acquired a second PUMA 260 and a PUMA 560 through the cooperation of the Adept Corporation. The PUMA has a general six degrees-of-freedom articulated form, and hence its dynamic and kinematic characteristics are similar to those which are likely to be found on space systems. It is also quite similar to the PUMA manipulators being used by the Langley Automation Branch in their work. Finally, because of their light weight, problems associated with mounting these manipulators on our vehicle emulator are reduced.

In order to use the PUMA to study advanced control algortihms we replaced its closed architecture industrial controller with a PDP 11/73 microcomputer which can be programmed in a relatively high level languages, such as PASCAL (see Figure 3). The PUMA is interfaced with the PDP 11/73 through specially designed and built interface boards, called Dac Trackers. A complete description of this control manipulator test system, hardware and software, can be found in our past

Figure 3

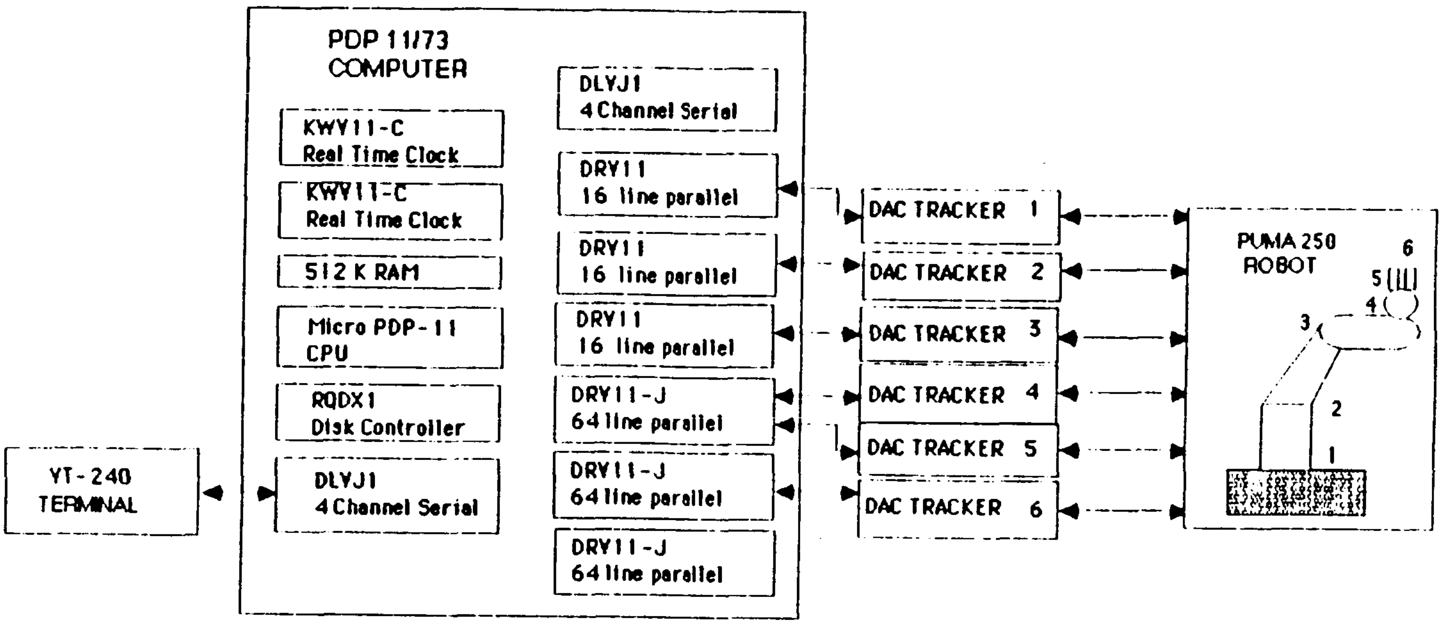

Figure 3: Manipulator Control Architecture

annual reports. This configuration has proven to be very effective in permitting us to experimentally study advanced control algorithms quickly. We have completed studies in which we have compared the system under a conventional PID controller, an advanced multi-axis adaptive controller (see Appendix I), and our sparse data model building learning controller. In the latter work we interfaced our Automatix's computer based vision system to the PUMA's PDP 11/73 control computer.

Since this hardware configuration proved so effective we have used a Digital Equipment Grant to acquire several additional PDP 11/73's which were used for data acquisition and control of the moving base emulator system described below.

2. One DOF Vehicle Emulator System

During the last year of the program we developed and demonstrated a concept for emulating the dynamic characteristics of a manipulator mounted on a free floating spacecraft. We designed, constructed and tested a one degree-of-freedom computer controlled system, called a Vehicle Emulator System (VES). It is a hydraulically powered platform with a ten inch vertical excursion, see Figure 4. The motion of the platform is computer controlled to provide arbitrary base motion as a function of time. It can carry our PUMA 260 manipulator and permit us to study the dynamic interactions between the manipulator and platform. The base emulator's electronic interfaces are compatible with the manipulator control computer to permit study of the vehicle-manipulator interactions more easily, see Figure 5. A force feedback control loop allows the mechanical admittance of the platform to be varied over a wide range to emulate different base vehicle dynamic properties. The dynamics of the moving base emulator have been successfully simulated on the computer and experimentally verified.

3. Six DOF Vehicle Emulator Design

Based on our successful experience with the one degree-of-freedom system we have designed a six degrees-of-freedom VES based on the Stewart mechanism. The system will have six electrohydraulic computer controlled actuators and has been designed to to carry either a PUMA 260 or 560 when emulating free floating conditions, like those found in space, see Figure 6. The computer architecture of the platform controller has been designed, see Figure 7. It is also based on a PDP 11/73 computer. Individual pistons will be controlled with KXT11 computer boards. The controllers use position, acceleration and force sensors in the control loop. The hydraulic cylinders and their parts, pistons, servo valves, potentiometers, bearings, 6 DOF force sensors and servo controller components, have been purchased.

This design should enable the PUMA to reach most of its workspace while the platform is emulating a zero gravity environment. The interactions of this platform with the PUMA are through a force sensor which is mounted between them. We have considered several methods for compensating the gravity forces and moments acting on the PUMA.

Figure 4

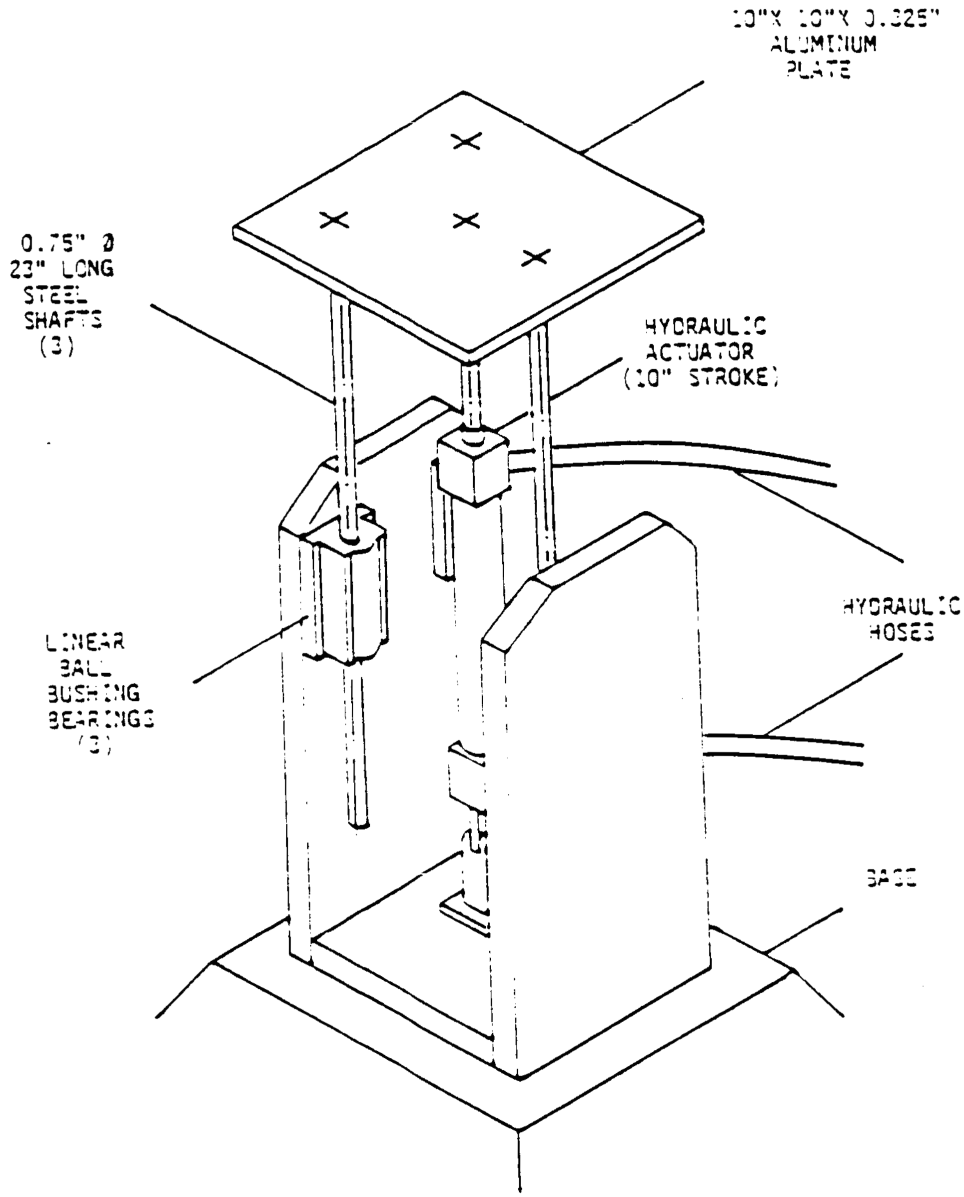

Figure 4: One Degree-of-Freedom VES Mechanical Design

Figure 5

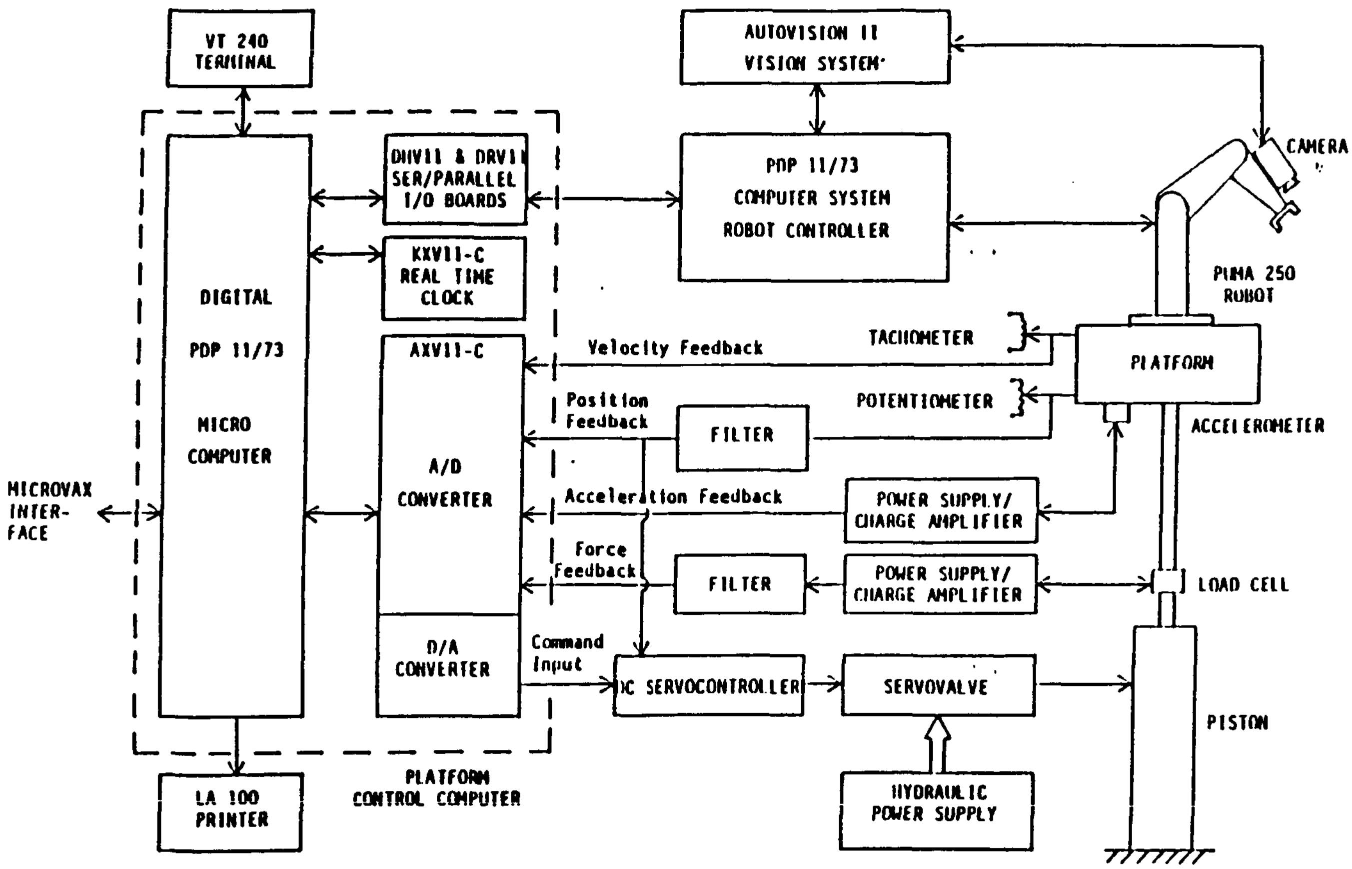

Figure 5: One Degree-of-Freedom Controller Architecture

Figure 6

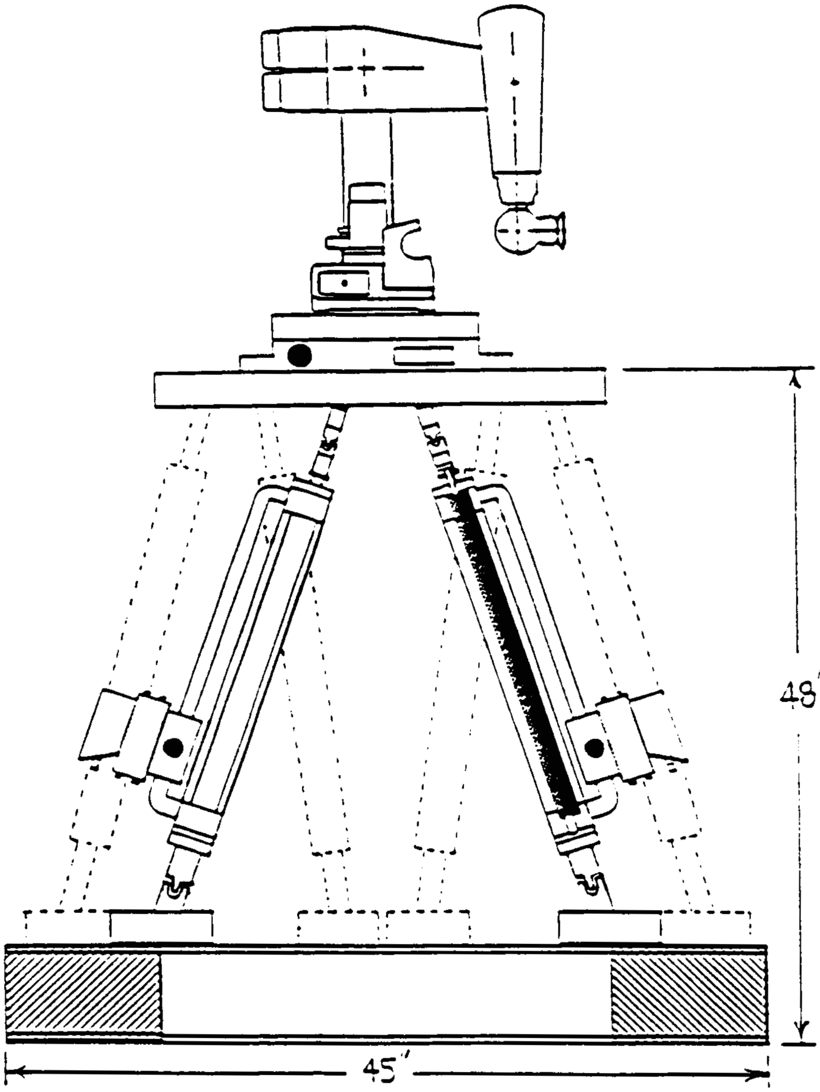

Figure 6: Six Degrees-of-Freedom VES Mechanical Design

Figure 7

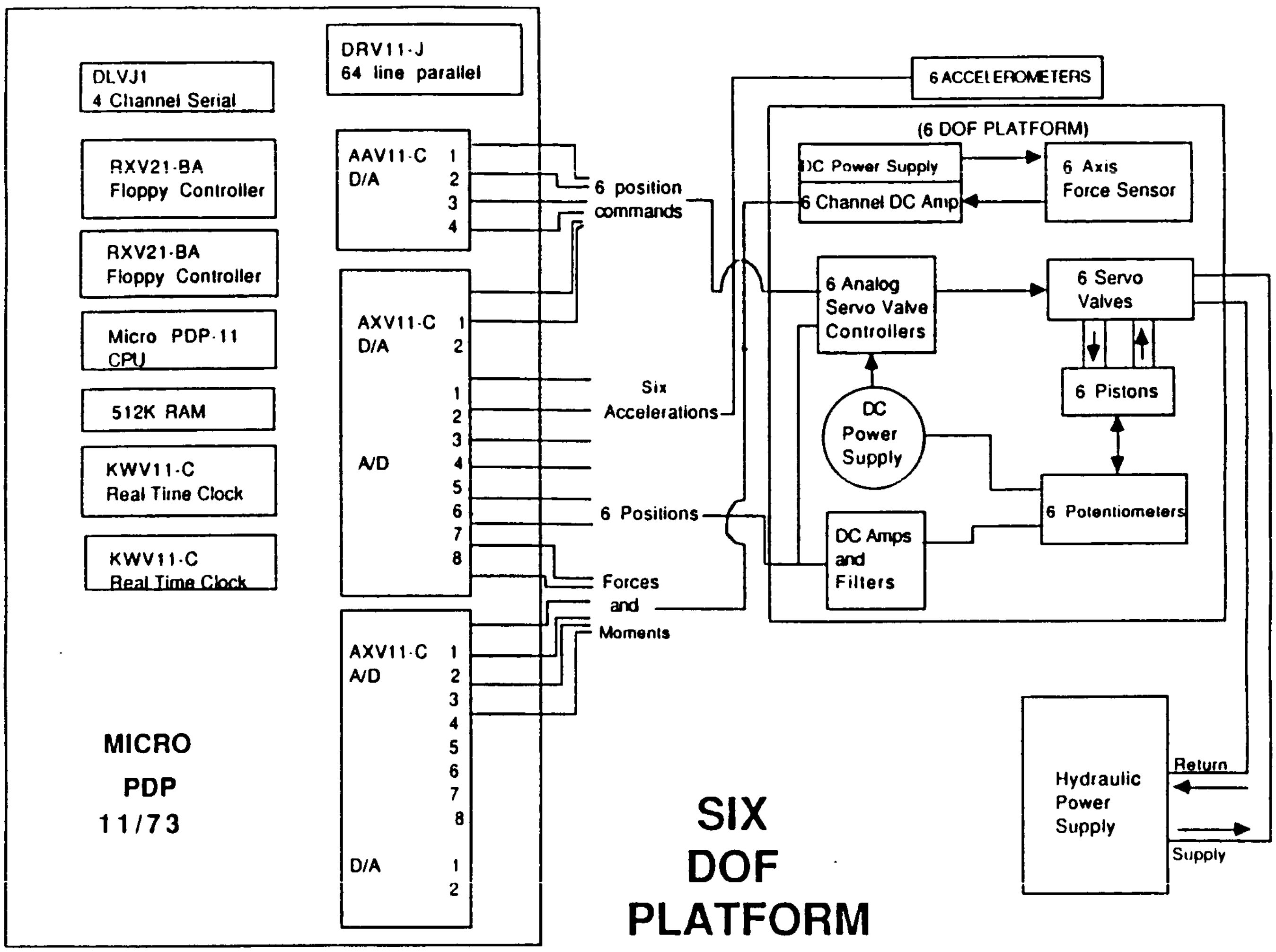

Figure 7: Six Degrees-of-Freedom Controller Architecture

D. List of Recent Relevant Published Papers

Dubowsky, S. and Shiller, Z., "Optimal Dynamic Trajectories for Robotic Manipulators," Proceedings of the Fifth CISM-IFToMM Symposium on the Theory and Practice of Robots and Manipulators, Udine, Italy, June 1984. Published by the MIT Press, pp. 133-143, First edition 1985.

Dubowsky, S. and Kornbluh, R., "On the Development of High Performance Adaptive Control Algorithms for Robotic Manipulators", Proceedings of the Second International Symposium of Robotics Research, August 1984, Kyoto, Japan, published by the MIT Press.

Shiller, Z. and Dubowsky, S., "On the Optimal Control of Robotic Manipulators with Actuator and End-Effector Constraints," Proceedings of the IEEE International Conference on Robotics and Automation, pp. 614-620, St. Louis, Missouri, March 25-28, 1985.

Dubowsky, S., "Active Control of Mechanical Systems: The State-of-the-Art for Robotic Manipulators," Proceedings of AIAA 26th Structure, Structural Dynamics and Materials Conference, pp. 258-261, Orlando, Florida, April 15-17, 1985 (Invited).

Dubowsky, S., "The Multi-Body Mechanics of Manipulators," Proceedings of the NASA Workshop on Computational Structural Mechanics, Langley Research Center, Hampton, Va, June 18-20, 1985 (Invited).

Bobrow, J.E., Dubowsky, S., and Gibson, J.S., "Time-Optimal Control of Robotic Manipulators," The International Journal of Robotics Research, Vol. 4, No. 3, Fall 1985.

Dubowsky, S. and Blubaugh, T.D., "Time Optimal Robotic Manipulator Motions and Work Places for Point to Point Tasks," Proceedings of the 24th IEEE Conference on Decision and Control, Fort Lauderdale, Florida, December 11-13, 1985. Accepted for publication in the IEEE Journal of Robotics and Automation (Invited).

Dubowsky, S., Norris, M.A. and Shiller, Z., "Time Optimal Trajectory Planning for Robotic Manipulators with Obstacle Avoidance: A CAD Approach," Proceedings of the 1986 IEEE International Conference on Robotics and Automation, San Francisco, CA, April 7-10, 1986.

Dubowsky, S., Norris, M.A. and Shiller, Z., "Time Optimal Robotic Manipulator Task Planning," Proceedings of the Sixth CISM-IFToMM Symposium on Theory and Practice of Robots and Manipulators - ROMANSY '86, September 9-12, 1986, Cracow, Poland. (Invited)

Dubowsky, S. and Vafa, Z., "A Virtual Manipulator Model for Space Robotic Systems," Proceedings of NASA Workshop on Space Telerobotics, Jan. 20-22, 1987, Jet Propulsion Lab., CALTECH., Pasadena, CA.

Dubowsky, S., Deck, J.F. and Costello, H., "The Dynamic Modeling of Flexible Spatial Machine Systems with Clearance," Journal of Mechanisms, Transmissions and Automation in Design, ASME Tractions, Vol 109, No. 1, March 1987, pp 87-94.

Vafa, Z. and Dubowsky, S., "On the Dynamics of Manipulators in Space Using the Virtual Manipulator Approach," Proceedings of the 1987 IEEE International Conference on Robotics and Automation, March 30-April 3, 1987, Raleigh, North Carolina.

Morita, A., Dubowsky, S. and Hootsmans, N.A.M., "Learning Control for Robotic Manipulators with Sparse Data," Proceedings of the 1987 American Control Conference, Minneapolis, MN, June 10-12,1987.

Shiller, Z. and Dubowsky, S., "The Acceleration Map and its Use in Minimum Time Motion Planning of Robotic Manipulators," Submitted to 1987 ASME International Computers in Engineering Conference and Exhibition, New York, NY, August 9-13, 1987.

Vafa, Z. and Dubowsky, S., "Kinematic and Dynamic Models of Manipulators for Use in Space: The Concept of the Virtual Manipulator," Proceedings of the Seventh World Congress on the Theory of Machines and Mechanisms, Sevilla, Spain, September 17-22, 1987.

E. A List of Recently Completed Relevant Theses
(See Appendix X for abstracts)

Whaley, J.L., "Model-Referenced Adaptive Control of a Two Degree-of-Freedom Robotic Device", January 1984, BS Thesis.

Brooks, N., "Kinematics of Robotic Manipulators in Confined Environments" June 1984, BS Thesis.

Norris, M.A. "Spatially Optimal Path Planning for Robotic Manipulators with Obstacle Avoidance and Joint Motion Contraints" May 1985, BS Thesis.

Lynch, R. "Analysis of the Dynamics and Control of a Two Degree-of-Freedom Robotic Manipulator Mounted on a Moving Base" October 1985, MS Thesis.

Whaley, J.L. "An Experimental System for Testing Robotic Manipulator Control Algorithms: A Demonstration of Adaptive Control" November 1985, MS Thesis.

Morita, A. "A Study of Learning Controllers for Robot Manipulators with Sparse Data" February 1986, MS Thesis.

Covell, D.N. "Robotic Acquisition and Manipulation of Moving Objects Using Sparse Vision Information" May 1985, MS Thesis.

Fresko, M. "The Design and Implementation of a Computer Controlled Platform with Variable Admittance" January 1987, MS Thesis.

Tanner, A.B. "Study of Robotic Manipulators Subjected to Base Disturbances" January 1987, MS Thesis.

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V. REFERENCES

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